On the climatology and structure of tropical cyclones in the Australian/southwest Pacific region: III. Major hurricanes

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An Australian region intensity change climatology is presented. The climatological and structural features of major hurricanes are then described and a comparison is made with the oceanic hurricane from the two companion papers (Holland 1983b, 1983c). The two systems are shown to have similar structures and environmental interactions. This paper concludes the study on the climatology and structure of tropical cyclones throughout the Australian/southwest Pacific region. Hence, an overall summary of the major findings is also presented.

Introduction

This is the last of three papers aimed at examining the major climatological and structural features of tropical storms, hurricanes and major hurricanes throughout the Australian/southwest Pacific region.

In the previous two papers (Holland 1983b, 1983c; hereafter referred to as H1 and H2) we discussed tropical storms and hurricanes. Here we present a climatology and structure of the major hurricane, together with some statistics on intensity change. Unfortunately, we do not have sufficient information to incorporate the southwest Pacific east of 165°E; hence our discussion is limited to the Australian region (105°-165°E). Some additional climatological information on major hurricanes in the neglected portion of the southwest Pacific region may be found in Revell (1981).

In summary, we then present an overview of the findings from all three papers and indicate some future research avenues.

Data and definitions

The data, compositing methodology and special definitions described in H1 also form the basis of this paper. In particular, we have defined major hurricanes as all cyclones in which the minimum central pressures were below 960 mb. Using Dvorak (1975) these systems correspond to class 3-5 hurricanes on the Saffir-Simpson scale (Simpson 1974) and to supertyphoons in the northwest Pacific region. This definition is also consistent with the major hurricane classification of Revell (1981).

Following Holland (1981) we also place tropical cyclone tracks into five categories: westward, southward and eastward moving, recurving and erratic. The first three describe cyclones which moved continuously towards the west to southwest, southwest to southeast, and southeast to east throughout their lifetime, with no major track perturbations. To be classified as recurving a cyclone must have moved steadily to the west or southwest for at least two days, recurved in an anticlockwise manner, then moved steadily east to southeast for another two days (or crossed the coast). All cyclones which do not fit the above classification were placed in the erratic category.

In interpreting the climatological results in this paper, careful attention should be given to the inherent data problems and deficiencies described in H1 and H2.

Major hurricane climatology

Spatial distribution

The major hurricanes form a subset of the hurricanes and, as shown in Fig. 1, have a very similar spatial distribution to that presented in H2. They occur most frequently off the northwest Australian coast, with secondary maxima in the Gulf of Carpentaria and Coral Sea region. The origin, maximum intensity and decay point distributions, shown in Fig. 2, are also qualitatively similar to those for the hurricane. Note, however, the concentration of coastal crossings along the northwest Australian coast. Eighty-six per cent of major hurricanes in the north/west Australian region made landfall compared to only 38 per cent of non-major hurricanes and 55 per cent of tropical
over the north/west Australian region. This arises partly from a mixing of Coral Sea systems with those in the north/west Australian region. But there is also tentative evidence that a higher proportion of hurricanes become major in this mid-season period.

**Motion**

The trend for hurricanes to move more consistently westward than tropical storms (H2) is continued in the major hurricane classification. As Fig. 4 shows, major hurricanes in the Australian region are

**Intra-seasonal distribution**

The intra-seasonal distribution of major hurricanes is shown in Fig. 3. Because of the small number of observations, no statistical significance can be placed on any of the details shown in Fig. 1. However, the major hurricanes display the same early season maximum as the larger hurricane distribution in H2; thus, this is probably a real feature. By comparison, there is no ready explanation for the March minimum and this may well be due to data bias.

Note that there is no distinct mid-season minimum in major hurricanes, as was observed for hurricanes dominated by west to southwestward moving systems. A similar finding has been made for the southwest Pacific by Revel (1981). We shall, however, show presently that these major hurricanes are comprised mainly of recurring cyclones which cross the Australian coast after recurvature. Australian region cyclones which move continuously westward rarely become major hurricanes. This is quite different to observations in other ocean basins where westward moving systems, which can move for long periods over warm tropical waters with no detrimental shearing effects by strong upper tropospheric westerlies, may become very intense.

The speed distribution, including the mean and median speeds, is almost identical to that for north/west Australian hurricanes described in H2.

**Tropical cyclone intensity and intensity change**

Recall from the definitions in H1 that tropical cyclone intensity refers to the maximum wind or minimum central pressure only. The radius of gale force winds, or outer closed isobar, defines the cyclone size, and strength refers to the average angular momentum inside 300 km. At this stage of our investigation we have not been able to develop a climatology of strength or size for the Australian region. Hence, we limit our presentation here to a description of the intensity and intensity change features only.

The maximum intensity distribution for tropical cyclones over the Australian region is shown in Fig.
5. The distribution curve gives the number of cyclones with minimum central pressures lying in overlapping 5 mb bands (1 mb resolution), and has also been smoothed by a running 5-point mean. We see that over the entire region, 85 per cent of tropical cyclones reached hurricane intensity and 15 per cent became major hurricanes. The proportions for the north/west Australian region and the southwest Pacific taken separately are similar. However, in the north/west Australian region most tropical storms are found in the Gulf of Carpentaria and most hurricanes off the northwest Australian coast. Hurricanes with central pressures less than 940 mb also occurred exclusively off the northwest Australian coast; the corresponding lack of very severe cyclones over the Coral Sea may be real or it may be a result of the possible data bias in this region described by Holland (1981).

As we have shown in Holland (1983a), if all cyclones are considered together there is no significant correlation between maximum intensity and the latitude at which the cyclones formed. However, significant trends emerge if we separate tropical storms from hurricanes and plot minimum central pressure against origin latitude. As may be seen in Fig. 6, the most intense hurricanes tend to originate around 10°S in the Coral Sea region and at a higher latitude of 15°—18°S in the north/west Australian region. Notably, in both regions, cyclones which originate at very low latitudes do not become as intense as those which originate at higher latitudes.

As shown in Fig. 7, there are also significant trends in the maximum intensity distribution of intensification period and mean intensification rate (from origin to maximum intensity). Comparing tropical storms (980-995 mb) to major hurricanes (960 mb), we see that the major hurricanes typically take twice as long to reach maximum intensity and also intensify at three times the rate of tropical storms. The tropical storm portion of both curves in Fig. 7 lies between the slow and typical development curves of Dvorak (1975). But, the hurricanes are quite different: between 980 and 940 mb they lie very near Dvorak’s rapid development curve. Though there are very few observations below 940 mb, the intensification rates seem to level off indicating that these very severe systems simply manage to maintain a longer intensification period.

It is also interesting that below 970 mb the time to maximum intensity, and the intensification rate curves, are distinctly out of phase. This implies that either the ultimate intensity of each hurricane was somehow predetermined (regardless of intensification rate) or, that whatever processes cause rapid intensification also hasten the eventual destruction of the cyclone.

The latitudinal distribution of the local rates of intensification (6-hour resolution and exclusive of
landfalling storms) of those cyclones which became hurricanes is shown in Fig. 8. In both regions decaying systems dominate polewards of 22°S. In the Coral Sea region the average intensification rate is essentially constant equatorwards of 20°S, whereas in the north/west Australian region a significant maximum occurs between 15°-20°S. By comparison, tropical storms (not shown) also have a preponderance of decaying systems polewards of 20°S. But, equatorward of this latitude they exhibit an almost zero net intensification rate, a result of deepening and filling systems occurring in nearly equal proportions. Thus, while hurricanes typically decay in the subtropics, a large proportion of tropical storms decay over the tropical oceans.

The mean meridional and zonal motion for tropical storms and all hurricanes during intensification is contained in Table 1. In both regions hurricanes move more rapidly westward than tropical storms, and in the southwest Pacific tropical storms tend to move eastward during intensification. Surprisingly, intensifying hurricanes in both regions move poleward faster on an average than intensifying tropical storms. Revell (1981) obtained different results for the entire southwest Pacific from 1969 to 1979. He found that tropical storms (which he defines as being greater than 25 m s⁻¹ maximum wind speed) moved eastward at 3.6 m s⁻¹ and poleward at 2.6 m s⁻¹ while hurricanes move westward at 0.8 m s⁻¹ and poleward at 1.9 m s⁻¹. As we have already shown in H1, this difference is due to the distinct increase in poleward and eastward motion for tropical storms east of 165°E.

A quite important finding of this study is the distinction between track types and cyclone intensity shown in Fig. 9. This figure contains the maximum
Fig. 8 Distribution by latitude of local intensification rates for the complete life cycle of hurricanes in the Australian region. Ninety-five per cent confidence intervals are also shown.

![Graph showing distribution by latitude of local intensification rates for hurricanes.]

Table 1. Mean zonal ($V_E$) and meridional ($V_N$) motion (m s$^{-1}$) during the intensification period of tropical storms and hurricanes in the north/west Australian region and southwest Pacific region west of 165°E.

<table>
<thead>
<tr>
<th>Region</th>
<th>Intensity</th>
<th>$V_E$</th>
<th>$V_N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>North/west Australian</td>
<td>Tropical storms</td>
<td>-1.1</td>
<td>-1.0</td>
</tr>
<tr>
<td></td>
<td>Hurricanes</td>
<td>-2.0</td>
<td>-1.5</td>
</tr>
<tr>
<td>Southwest Pacific</td>
<td>Tropical storms</td>
<td>0.5</td>
<td>-2.0</td>
</tr>
<tr>
<td>region west of 165°E</td>
<td>Hurricanes</td>
<td>-0.6</td>
<td>-2.4</td>
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Rapid intensification

Periods of extreme rapid intensification are certainly underestimated in the Australian region. This results from the almost universal use since 1966 of satellite techniques (Anderson et al. 1974; Dvorak 1975) in which intensity change is limited as much as possible to two or three characteristic rates. Hence, using Dvorak (1975) as a basis, we define rapid intensification as any period in which the central pressure fell by at least 6 mb in a 6-hour period, and a rapid intensification cycle as the period in which the central pressure continued to fall at a minimum rate of 6 mb for subsequent 6-hour periods. The distribution of total central pressure fall during these rapid intensification cycles is shown in Fig. 10. A large number of single event 6 mb falls were recorded; and some of these were quite suspect, occurring just before landfall or as the cyclone crossed an observation point. The largest sustained rapid pressure falls were two observations of 48 mb over periods of 36 and 42 hours; nothing even approaching the occasional northwest Pacific pressure falls of 40-90 mb in 24 hours (Holliday and Thompson 1979) has been recorded in the Australian region.

Fig. 9 Percentage frequency of maximum intensity for tropical cyclones in the westward, eastward, erratic and recurving movement classes (see text for definitions).
The distributions of central pressure, latitude and month at which rapid intensification commenced are shown in Figs 11, 12 and 13. Rapid intensification typically started around 995 mb for both single and multiple period cycles and in 75 per cent of cases ended within 12 hours of maximum intensity. A secondary peak may be seen at the 970-975 mb central pressure band and almost no rapid intensification cycles began below 970 mb. The mean latitude of commencement is near 15°S and the distribution is skewed towards higher latitudes. All of the low latitude observations occurred in the early or late part of the season, but the general distribution is normally distributed throughout the season.

Fig. 10 Distribution, in 6 mb classes, of total falls in central pressure during rapid intensification cycles for Australian region hurricanes.

![Graph showing central pressure falls](image1)

Mean 18 mb
Median 13 mb

The mean and median cyclone speeds at the start of rapid intensification were 4.1 and 3.6 m s⁻¹ respectively; these are slightly slower than the mean speed of all hurricanes. With regard to direction of motion: 41 per cent recurved within 24 hours of the rapid intensification cycle; 10 per cent displayed evidence of a missed recurvature; 16 per cent moved continuously westward; 21 per cent moved eastward, the majority of which accelerated by more than 5 m s⁻¹ within 24 hours of the rapid intensification cycle; 6 per cent moved continuously southward; and 6 per cent were distinctly erratic. These proportions are quite similar to the hurricane distribution in Fig. 9, an expected result since most hurricanes experience a period of rapid intensification.

The dynamic structure of major recurring hurricanes

We have shown in Fig. 9 that most major hurricanes also recurve. This not only implies a consistent environmental influence, it also enables us to produce a dynamic composite of most major hurricanes in the Australian region while minimising any bias problems. To do this, we selected all major Australian hurricanes (minimum central pressure less than 960 mb) which recurved and which reached maximum intensity at or within one day of recurvature. These were separated into three phases: the developing storm phase, with central pressure between 995 and 980 mb (AUS01); the intensifying hurricane phase, with central pressure less than 980 mb (AUS02); and the decaying hurricane phase, again central pressure less than 980 mb, no landfalls, and at most two days after maximum intensity was reached (AUS03). Further details on these composites may be found in Holland (1983a).

We note that the major hurricanes which comprise this composite come from both the eastern and
western Australian regions. We have assumed that the narrow stratification criteria imply a consistent environmental wind field, and thus minimise any wind bias. However, the wide longitudinal range of the observations, with the presence of the Australian continent, stop us from also producing an acceptable thermal composite.

**Axisymmetric cross-sections**

The axisymmetric cross-sections of azimuthal winds for the different phases of the major recurving hurricane are shown in Fig. 14. Also shown for comparison are the azimuthal winds for the oceanic hurricane composite described in H1 and H2. We note that these two composites are completely independent of one another.

In the tropical storm phase (AUS01, AUS09) the two systems are almost identical. They are both quite large and have an extensive upper anticyclonic flow. However, the tropical storm phase of the major recurving hurricane does have a slightly deeper cyclonic circulation, with a more concentrated vertical wind shear in the upper troposphere.

In the intensifying hurricane phase (AUS02, AUS06) the major recurving hurricane is more intense than the oceanic hurricane. This is to be expected, but, interestingly, the major recurving hurricane is also weaker and smaller; the oceanic hurricane has both strengthened and grown, whereas the strength and size of the major recurving hurricane has remained static. Note also that there is virtually no change in the extent or strength of the upper tropospheric anticyclonic flow between the intensifying tropical storm and hurricane phases of both systems. We shall presently see (Figs 16 and 17) that this consistent, axisymmetric anticyclonic circulation is maintained by strong subtropical westerlies on the cyclone’s poleward side.

In the decaying hurricane phase (AUS03, AUS07) the major recurving hurricane has become less intense, but has strengthened and grown slightly. Indeed, it is now much stronger than the decaying oceanic hurricane, which has weakened considerably. This may be an actual regional difference, but it may equally be a composite bias problem; since many of the decaying major recurving hurricanes crossed the Australian coast, the AUS03 composite is, in the mean, not as far into the decaying phase as is the AUS07 oceanic system. A general disruption of the upper tropospheric anticyclonic circulation is also observed for both systems and the deep cyclonic circulation of the intensifying hurricane phase has changed to a distinct low-level maximum with an increase in mid-tropospheric vertical wind shear.

The reasons behind these azimuthal wind variations may be partially seen in the axisymmetric radial wind cross-sections of Fig. 15.

Both systems have a long, shallow outflow layer near 200 mb during intensification with inflow maxima immediately above and below. As we have noted in H1 and H2, differential angular momentum transports by these radial winds help generate and maintain the observed deep cyclonic circulation and strong upper tropospheric vertical wind shear (Fig. 14). The two hurricanes then decay with a deep outflow and concomitant disruption of the mid to upper tropospheric structure.

In the tropical storm phase the major recurving and oceanic hurricane further exhibits a significant outflow near 600 mb and out to 4 degrees latitude radius, and low-level, outer region inflow. The outer region inflow provides the necessary import of cyclonic angular momentum for the large size of these two systems. It is notable that the inflow disappears at the intensifying major recurving hurricane phase and there is essentially no strength or size change from the tropical storm phase (Fig. 14). However, the inflow is maintained in the intensifying oceanic hurricane phase and there is a concomitant size and strength increase (Fig. 14).

Notably, the major recurving hurricane has the strongest low-level inner region inflow at all phases. We believe that this is largely a result of increased surface frictional dissipation over the Australian continent.

A more comprehensive discussion of the importance of these axisymmetric features, and their maintenance mechanisms, may be found in Holland and Merrill (1983).

**Plan view wind fields**

Plan view streamline/isotach fields for the three phases of the major recurving hurricane are shown in Figs 16 to 18. The geographical background is to add perspective; the cyclones are located at the mean latitude of their components and at typical longitudes...
Fig. 14 Axisymmetric cross-sections of azimuthal winds for the major recurring hurricane (AUS01, AUS02, AUS03) and oceanic hurricane (AUS09, AUS06, AUS07; after H1 and H2). AUS01 and AUS09 are the tropical storm phases; AUS02 and AUS06 are the intensifying hurricane, and AUS03 and AUS07 the decaying hurricane phases. Regions of anticyclonic circulation are hatched.
Fig. 15 Axisymmetric cross-section of radial winds for the major recurving hurricane (AUS01, AUS02, AUS03) and the oceanic hurricane (AUS09, AUS06, AUS07; after H1 and H2). AUS01 and AUS09 are the tropical storm phases; AUS02 and AUS06 are the intensifying hurricane, and AUS03 and AUS07 the decaying hurricane phases. Outflow regions are hatched and radial winds of less than 1 m s⁻¹ are not significantly different from zero.
of recurving cyclones off the western Australian coast.

During all phases the major recurving hurricane has many similar characteristics to those described for the oceanic hurricane in H1 and H2. There are, however, a few differences.

The tropical storm in Fig. 16 is equatorwards of the subtropical ridge at all levels. Thus, the ubiquitous upper level subtropical westerlies lie some 8 to 10 degrees latitude polewards of its centre. Yet, an incipient outflow jet to these westerlies has formed in the southeast. Also present is a distinct westward outflow at 150 mb. Interestingly, however, the major equatorward flow does not emanate from the storm; rather it appears to originate from convective activity further east along the monsoonal trough.

The outflow jet connection to the subtropical westerlies is well established by the time the major recurving hurricane enters its intensifying hurricane phase (Fig. 17). The hurricane has now crossed the subtropical ridge above 500 mb and is entering a strongly sheared environment, with a mean upper tropospheric westerly flow overlying a lower-level easterly flow. Indeed, at this stage the hurricane is experiencing a weak net north/northwesterly flow, even though it continues to move on a southwestward course (Holland 1983e).

As the hurricane recurves it moves into an increasingly sheared environment (Fig. 18). A mean easterly flow remains at 850 mb but, strong westerly winds extend through the hurricane at 500 mb and above. These westerly winds disrupt the upper structure and a rapid decay to a shallow depression occurs.

Conclusions

In this and two companion papers (H1 and H2) we
have documented the completed first stage of a collaborative project between Colorado State University and the Australian Bureau of Meteorology to study tropical cyclones in the Australia/southwest Pacific region. We have used a variety of sources to gather all available cyclone and environmental data for the period 1958-1979. Further, we have adapted Professor Gray's compositing routines to a southern hemispheric perspective, and have incorporated new statistical and climatological techniques. These new techniques have been very useful in the stratification and analyses stages.

Using these data and new routines, we have provided a comprehensive description of the major climatological and structural features of tropical storms and hurricanes throughout the region. We have further documented some interesting environmental effects.

**Climatology**

The tropical cyclone season extends primarily from November to May, though unseasonal cyclones occasionally occur in other months. Within the season, tropical storms rise to a mid-season maximum followed by a secondary, late season peak. Hurricanes, however, exhibit an early season maximum and those in the northwest Australian region have a mid-season minimum. We have attributed this mid-season minimum (which does not appear in the tropical storm distribution) mainly to the detrimental effect of the Australian continent, with most cyclones forming very close to the coast and in the Gulf of Carpentaria. But changing environmental flow fields may also have an affect.

The Australian continent also contributed to distinctive variations in the spatial distributions of tropical storms and hurricanes. Tropical cyclones
Fig. 18(a) Plan view streamline/isotach (m s⁻¹) fields for the decaying hurricane phase of the major recurving hurricane at 850 and 500 mb.

Fig. 18(b) Plan view streamline/isotach (m s⁻¹) fields for the decaying hurricane phase of the major recurving hurricane at 250 and 150 mb.

have been observed throughout the region from 105°E to 150°W but the occurrence peaks, and relative hurricane/tropical storm proportions, vary considerably. The highest tropical storm frequency occurs in the land-locked Gulf of Carpentaria, with secondary maxima in the Coral Sea and off the northwest Australian coast. By comparison, hurricanes have a very high frequency off the northwest Australian coast, occur only occasionally in the Gulf of Carpentaria, and are spread more widely throughout the southwest Pacific. The relative proportions of hurricane to tropical storm occurrence are 70/30 off the northwest Australian coast, 20/80 in the Gulf of Carpentaria, and 50/50 in the southwest Pacific. These proportions reflect both the number of systems and their lifetime.

We have thus observed a unique situation in that both the highest frequency and proportion of intense systems occurs off the west coast of a large continent. Indeed, around 40 per cent of all major hurricanes in the entire region occur just off, and make landfall on, the northwest Australian coast. Contributing factors to this behaviour include: the warm ocean temperatures there; the interaction with hot continental air, which helps steer cyclones along and just off the Australian coast; and the prevailing flow fields, in which the cyclone is embedded in a deep low-level tropical environment but can still interact with the subtropical westerly flow in the upper troposphere. The mechanisms of intensification by this westerly flow interaction are discussed in Holland and Merrill (1983).

The overall proportions of major hurricanes, all hurricanes, and tropical storms in the Australian region is 15/45/55 respectively. Insufficient information was available to enable us to distinguish
major hurricanes east of 165°E, but Revell (1981) found similar proportions there for the period 1969-1979. The most intense hurricanes came from the recurring motion category. They typically originated near 10°S in the Coral Sea region and near 15°-18°S in the northwest Australian region; but many weaker tropical cyclones also form at these latitudes. The more intense systems generally intensify at a faster rate and take longer to reach maximum intensity; but this trend may be reversed for the very intense major hurricanes. Overall, then, tropical storms often form and decay over tropical waters, or over Australia; hurricanes tend to intensify while moving polewards to 20°-25°S then decay rapidly by crossing the coast; by becoming entangled in the strongly sheared subtropical westerlies; or by moving over a cold ocean surface.

Rapid intensification is certainly underestimated throughout the region. But most hurricanes follow the Dvorak (1975) rapid intensification curve and these typically come from the recurring motion category. Their rapid intensification cycle also starts either near 990-995, or 970 mb and ceases within 12 hours of maximum intensity. The seasonal and latitudinal distribution of rapid intensification events is similar to that for tropical cyclones generally.

Tropical cyclones in the southwest Pacific region move very differently to the classical pattern in other ocean basins. That is, the largest proportion tend to move eastward. This peculiar motion is a response to the low latitude, upper tropospheric westerlies and strongly sheared environment in this region. The Gulf of Carpentaria also has a majority of erratic and eastward moving systems. But most tropical cyclones off the northwest Australian coast move along the classical westward track or recurring parabola. This west coast movement is partially due to the prevailing flow there and partially due to interactions between the cyclone and the hot, dry air mass over northern Australia.

**Structure**

We have separately examined the structure of developing and non-developing oceanic tropical storms; of intensifying and decaying oceanic hurricanes; of hurricanes just off the east and west Australian coasts; and of recurring major hurricanes.

These cyclones have many similar features to those of the well documented northwest Pacific and North Atlantic systems. They are moist and warm cored, with a maximum temperature anomaly near 300 mb. An upper tropospheric anticyclone overlies a low to mid-level cyclonic circulation which extends beyond 1500 km radius. The vertical wind shear is concentrated near 300 mb in developing systems and spreads to lower levels as the cyclones decay. The secondary circulation displays the classical boundary layer inflow and upper tropospheric outflow regimes. Secondary inflow maxima occur in the lower stratosphere and near 400 mb, especially in developing cyclones, and there is evidence of a weak outflow near 600 mb in some cyclones.

The low-level circulation also exhibits a distinctive distortion, with a cyclonic extension to the west and convergence/anticyclogenesis to the east. We have surmised that this is the result of an interaction between the cyclone and the earth’s vorticity field which is reinforced by the concomitant development of a moist tropical feeder band on the equatorward and eastward side. Holland and Black (1983) provide a quantitative discussion of these features.

Further, there are a number of regional peculiarities which arise from the monsoonal environment, the close proximity of subtropical jet westerlies, and the effects of the Australian continent.

In the low levels, a distinct outer region inflow maximum is observed at the tropical storm stage. This inflow maximum arises from the development of surges in the monsoonal westerlies, as has been previously discussed by Love (1982), and/or trade wind easterlies. It leads to the characteristic large size of these systems, and, we believe, provides an optimum environment for development through the tropical storm stage.

The prevailing low latitude subtropical jet westerlies in this region, and especially over the southwest Pacific, provide very characteristic upper tropospheric structures. Developing tropical storms and intensifying hurricanes are typically close to, but not under, this westerly flow and are located between upstream trough and downstream ridge axes. Thus, in our mean composites we observe a marked confluence zone between the hurricane outflow and impinging westerlies some 600 km to the west and southwest of the centre. We also observe a long, intense outflow jet to the southeast. By comparison, decaying hurricanes, and especially non-developing tropical storms, over the southwest Pacific lie under the upper level westerlies. They are strongly sheared with convective activity displaced to the east and strong subsidence to the west.

Cyclones just off the east and west Australian coasts are also distinctly affected by the continent. In the east coast hurricanes the low-level winds are funnelled along the Great Dividing Range. Hence there is little inland penetration of moist tropical maritime air below 850 mb. Rather, dry continental air, which is advected off the continent and around the equatorward perimeter, tends to cut off the hurricane's tropical moisture supply.

West coast hurricanes are not so adversely affected. They are embedded in a deep tropical environment, moisture extends well inland over northwestern Australia, and the core is protected from the dry continental air. An unusual interaction does occur, however, as the hot continental air is advected off the coast on the cyclone's poleward side. Firstly, this produces a distinctly cold-cored structure
below 700 mb. Secondly, it introduces an equatorward directed temperature gradient, which, from thermal wind considerations (and observations), maintains a deep easterly flow over the cyclone core. Thus the cyclone/continental interaction helps maintain a long westward trajectory, just off the northwest coast.

Further research
Between this paper, H1 and H2, we have described a number of interesting climatological and structural features of tropical cyclones in the Australian/southwest Pacific region. Separate papers, Holland and Merrill (1983), Holland (1983d, 1983e) contain an examination of the mechanisms whereby these cyclones intensify, strengthen, grow and move. But this work is by no means complete; further research is needed and planned on the above mechanisms, together with the energetics and diurnal modulation of tropical cyclones and other weather systems in the Australian/southwest Pacific region. We believe that a continued exploitation of the environmental and cyclone data base, using the present analysis methodology and further improvements therein, will provide a significant increase in our understanding of these systems.

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References

Editor's Note: In this and the two other papers by Dr. Holland published in this issue reference is made to 'hurricanes' in the context of severe tropical cyclones of hurricane force in the Australian/southwest Pacific region. The Australian Bureau of Meteorology has no official classification of tropical cyclones as 'hurricanes' and the use of that term in the Australian Meteorological Magazine is that of the author, and does not, in any way, imply a change by the Bureau in the terminology of the Australian region. In fact, the matter has been carefully examined in recent years and Bureau policy is to continue the use of the term 'tropical cyclone'.